Effect of Tool Tilt Angle on Aluminum 2014 Friction Stir Welds

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Abstract

Friction Stir Welding (FSW) is an emerging solid state welding process gaining more applicability in various industries due to better quality of the joint as it has no effect on the parent metal. This process utilises a non-consumable rotating tool to generate frictional hat between tool and abutting surface of work piece to accomplish the weld. Being a solid state joining process, friction stir welding process offers various advantages like low distortion, absence of melt related defects, high joint strength etc., as compared to other conventional fusion welding techniques.An attempt has been made to study the influence of tool tilt angle on Aluminium 2014-T6 welds. A study on FSW of AA2014 Aluminium alloy at varying tool tilt angle ranging from 0 to 3 degrees at an interval of 0.5° and keeping other process parameters constant are presented in this paper. Present work also examines the force and torque during FSW with respect to defect development. This is due to owing to process parameters variation which results in variation in heat generation. The force on the pin in the metal flow direction (which is also called X-axis force) was correlated with defect formation, high X-axis force is recommended for defect free welds.

Index terms— friction stir welding, aluminium AA2014-T6 alloy, tool tilt angle, microstructure, force and torque analysis.

1 Introduction

riction Stir Welding (FSW) is a solid state welding process (i.e., the metal is not melted during the process) developed and patented by The Welding Institute (TWI), UK in 1991 [1], emerged as a new welding technique to be used in high strength alloys that are difficult to join with conventional fusion welding techniques. The process was initially developed for Aluminium alloys but since then FSW was suitable for joining large number of other metals [2]. Conventional fusion welding of aluminium alloys often produce a weld which suffers from defects, such as porosity, distortion developed as a consequence of entrapped gas not being able to escape from the weld pool during solidification process. In contrast, with FSW the interaction of non consumable rotating tool traversing along the joint line creates a welding joint through plastic deformation and consequent heat dissipation resulting temperatures below the melting point of the materials being joined. Other interesting benefits of FSW compared to fusion welding processes are low distortion, excellent mechanical properties in the weld zone, execution without a shielding gas and suitability to weld all aluminium alloys [3].

FSW can be used to produce Lap, Butt, Corner, T, Spot, Fillet and Hem joints, as well as to weld hollow objects, such as tanks and tubes/pipes, stock with different thicknesses, tapered sections and parts with 3dimensional contours ??2 & 4]. The technique can produce joints utilizing equipment based on traditional machine tool technologies, and it has been used to weld a variety of similar and dissimilar alloys along with welding metal matrix composites and to repair existing joints. Replacement of fastened joints with FSW joints can lead to significant weight and cost savings, attractive propositions for many industries [5]. The basic principle of friction stir welding process is remarkable simple. A rotating tool with pin and shoulder is inserted in the material to be joined and traversed along the joint line. The heating is localized and generated by friction between the rotating tool and work piece, with additional adiabatic heating from metal deformation [6][7]. The pin and shoulder of the tool can be modified in number of ways to influence material flow and micro structural formation.

Mishra and Ma et.al reported that the recent development of scrolled tool shoulder tool shoulder allows FSW with no tool tilt [8]. Chen et.al. investigated that under the same welding parameters, channel-like defects were observed in the welds produced in tool tilt angle below 1.5° and above 4.5° [9]. They also stated that the tool tilt angle has an essential influence on the heat input and the position of the defects in the weld. Kato et.al. observed defects in the weld when the tool tilt angle is 0° and above 3° [10]. Z.Barlas et.al. experimentally studied and reported that defect free welds obtained with a tool tilt angle 2°. [11]. Moneer et.al reported that optimum results were achieved with a tool tilt angle of 2° and tool offset 1mm [12].

2 II.

3 Experimental Procedure

The material used for this research study is aluminium AA2014-T4 alloy of 5mm thick with 50 mm width and 80mm length. Holes of similar depth were drilled along the sides of the sample. Two holes were drilled, one on either sides (advancing and retreating side) of the weld line, where thermocouples were inserted to measure temperature. Holes of 2mm diameter were drilled till a depth of 3 mm away from the weld centre. These holes were 1 mm below the surface of weld as shown in Fig. 1. Die steel (AISI-H13) is known for its excellent hot hardness. It gains its elevated temperature strength from precipitation of chromium, vanadium and molybdenum carbides upon hardening and tempering. The dissolution temperature of chromium, vanadium and molybdenum carbides is above 550°C which makes the material suitable for FSW tool material.

The equipment is a three-axis vertically configured Friction Stir Welding / Friction Stir Surfacing machine which accommodates a maximum plate size of 500 X 300 mm and has a maximum thrust of 50 kN on Z-axis. To maintain tool tilt angle during linear welding, the head can be tilted manually. The machine is controlled through a high-end CRIO (Compact Real Time) module PLC (Programmable Logical Controller) from National Instruments with Lab view software. The equipment can acquire and record the X-axis load / displacement, Y-axis load / displacement, Z-axis load / displacement and Spindle speed / Torque.

The temperature reached by each point at the end of the drilled holes were monitored and stored in Midi Logger GL900, equipment from GRAPHTEC. It is capable of obtaining multifunction inputs from its 8 channels. Long-term data can be captured directly to built-in flash memory or to an external USB memory stick at sampling intervals of from 1micro seconds to 1 minute. For high-speed sampling at intervals faster than 1micro second, up to one million data points can be captured to internal RAM (Random Axis Memory). The acquired or displayed data can be transferred directly to PC (Personal Computer).

Temperature is measured by K-type thermocouples connected to the equipment. K-type (chromel {90 percent nickel and 10 percent chromium} -alumel {95% nickel, 2% manganese, 2% aluminium and 1% silicon}) is the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C, chromel positive relative to alumel. It is inexpensive, and a wide variety of probes are available in its ?200°C to +1350°C / -328°F to +2462°F range.

FSW of AA 2014 plates were carried out at spindle speed 800 rpm, weld traverse speed 100 mm/min, tool downward feed 50 mm/min, plunge depth 4.8 mm and the force, torque data were acquired from the FSW equipment, for different tilt angle of tool: 0?, 0.5?, 1?, 1.5?, 2?, 2.5? and 3?. The temperatures attained by the different points were obtained from the temperature indicator ”Midi Logger”. From the obtained data, average forces and torques were calculated from the stabilized values. Also the highest temperature attained during each tilt angle was plotted against tilt angle.

The plates were then cut, to view the microstructures obtained at different regions along the width of the plate -WNZ (Weld Nugget Zone), HAZ (Heat Affected Zone) and TMAZ (Thermo Mechanically Affected Zone). Hot mounting was done to the cut samples, where Bakelite powder was used to mount the sample. Hot mounting was done on all the samples at 150°C and 290 bar pressure, with 2 minutes heat time and 4 minutes cool time. The samples were then polished using emery papers and diamond polisher. Finally kerosene cloth used to obtain final finish to be viewed under microscope. Keller’s reagent (190ml distilled water, 5ml HNO 3 , 3ml HCL and 2ml HF) used to etch the sample. The sample was then viewed under microscope and micrographs were captured at different location. Top surface of the weld shows surface defects on all welds made at different tool tilt angle except 1.5 0 and 3 0 tool tilt angle (Fig. 3).

4 Results and Discussion

Microstructure of weld shows internal cavity formation in all joints except the joint made at tool tilt angle of 3 o (Fig. **??**). The defect size reduces gradually from the lower tool tilt angle to higher tool tilt angle and vanishes at 3 o tool tilt angle (Fig. **??**). Types of defects observed in surface (Fig. 3.) and inside the weld (Fig. **??**.) can be considered as those which arise due to the lack of filling. Increase in tool tilt results in sharp increase in Z-torque, (Fig. **??**), X-load (Fig. 9) and Z-load (Fig. 11) with slight increase in temperature (Fig. 12). High torque, load and temperature indicate that the material is heated up to a wider extent and stirred adequately to fill the cavities left unfilled at low tool tilt angle. Increase of tool tilt angle also results in increase of forging action on the trailing edge of the weld thereby filling the cavities which otherwise remains at lower tool tilt angle.

J Typical microstructures at different locations of a weld at tool tilt angle of 3 o are shown in Fig. 6. The Weld Nugget Zone (WNZ) has experienced hightemperature and extensive plastic deformation, and is characterized by a dynamically re-crystallized, fine equiaxed grain structure (Fig. 6C). The Thermo-Mechanically Affected Zone (TMAZ) is created by plastic shear stress around the plastic flow of material and the grains are elongated along the direction of maximum shear stress.

The elongated grains are seen around the WNZ (Fig. 6 B & D). The Heat-Affected Zone (HAZ) is affected only by the thermal cycle without the role of mechanical stir, so the microstructure characteristic of the HAZ is coarse grains (Fig. 6 A & E). It can also be observed that in the advancing side, a clear boundary is visible in between TMAZ and WNZ, which is not observed in the retreating side (Fig. 6 B & D). Z torque increases with increase in tool tilt angle. Increase in tool tilt angle results in more heat generation and hence more material is plasticized which has to be stirred resulting in increase of z torque (Fig. **??**). Fig. **??** : Variation of Z torque Vs tilt angle ii. X-Load X-load is minimum during the initial plunging and dwelling period (Fig. **??**). Once the lateral movement of the tool starts an increase in X-load is observed as the tool has to move against the solid material ahead. Fig. **??** : Variation of X load Vs time X load increases gradually with increase in tool tilt angle (Fig. **??**) due to the following factors:

? With increasing tool tilt X component of Z-load increases continuously which adds to X-load.

? The pin of the tool is exposed more to the solid material.

? Due to the rise in temperature more material is plasticized, hence tool has to carry more material along with it during welding. iii. Z-Load Z-load continuously increases as the plunging starts. Two peaks are observed, first corresponding to full penetration of the pin while the second corresponds to rubbing of the shoulder (Fig. 10). Once the shoulder touches the material and starts dwelling, the material gets soften and Z-load drops till the steady state is reached when Z-load becomes uniform. Increase in Z-load with increase in tool tilt angle is observed (Fig. 11). This increase in Z-load can be attributed to effective increase in plunge depth (plunging of shoulder) at the trailing edge of weld. Increase in plunge depth due to the shoulder results in increased forging action on the weld and there by filling the cavity generated at the surface or inside the welds at lower tool tilt angle. In general, it can be observed that temperature attained is higher in advancing side, than the retreating side (Fig. 12). This is because material flow and plastic deformation around tool is from advancing side to retreating side additional to friction heat under the shoulder that gives higher temperature. So, the slipping rate on the retreating side is lower than the slipping rate on the advancing side. This is the reason that the heat fluxes on the advancing sides are higher, which leads to the fact that the temperatures are higher in this region. Due to the difference in temperature profile in advancing and retreating side, difference in microstructure (Fig. **??**) is also observed between advancing and retreating side. c) X load increases gradually with increase in tool tilt angle because, i. With increasing tool tilt X component of Z-load increases continuously which adds to X-load. ii. The pin of the tool is exposed more to the solid material. iii. Due to the rise in temperature more material is plasticized, so tool has to carry more material along with it.

d) Increase in Z-load with increase in tool tilt angle is observed. This increase in Z-load can be attributed to effective increase in plunge depth (plunging of shoulder) at the trailing edge of weld. Increase in plunge depth due to the shoulder results in increased forging action on the weld and thereby filling the cavity generated at the surface or inside the weld.

e) Z torque increases with increase in tool tilt angle as increase in tool tilt results in more heat generation and hence more material is plastized which has to be stirred resulting in increase of z torque.

f) Temperature distribution during FSW is not uniform throughout the plate being welded. There is a difference in temperature attained by regions in advancing side and retreating side. In general, it can be observed that temperature attained is higher in advancing side, than the retreating side.

g) High tool tilt angle of around 3 o is recommended for welding AA 2014 aluminium alloy for the given value of feed 100 mm/min and speed 1000 rpm to get defect free welds. [1] [2]

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Figure 1: Fig. 1 :

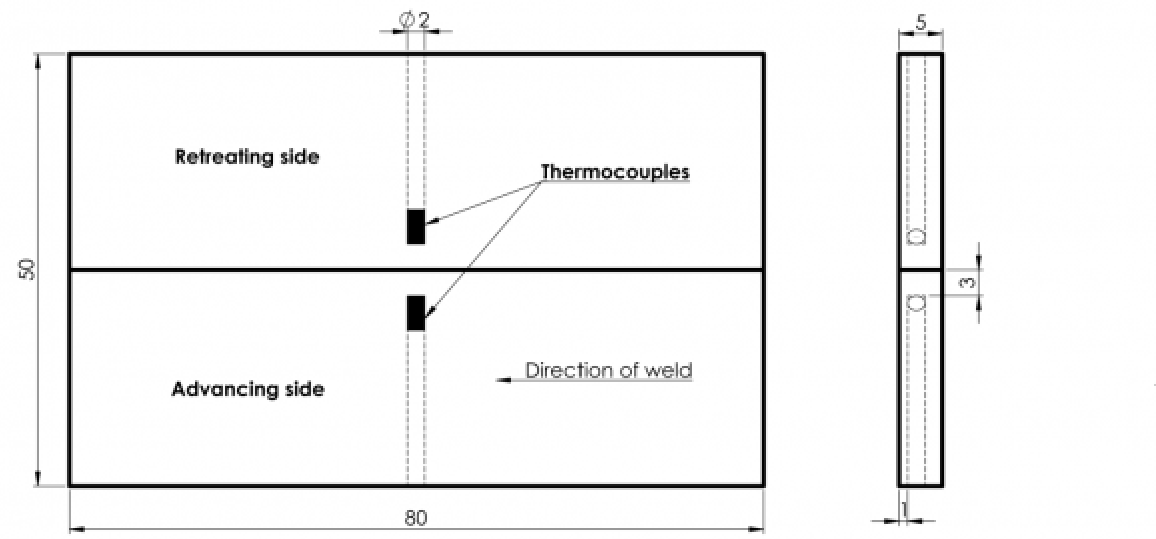

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Figure 2: Fig. 2 :

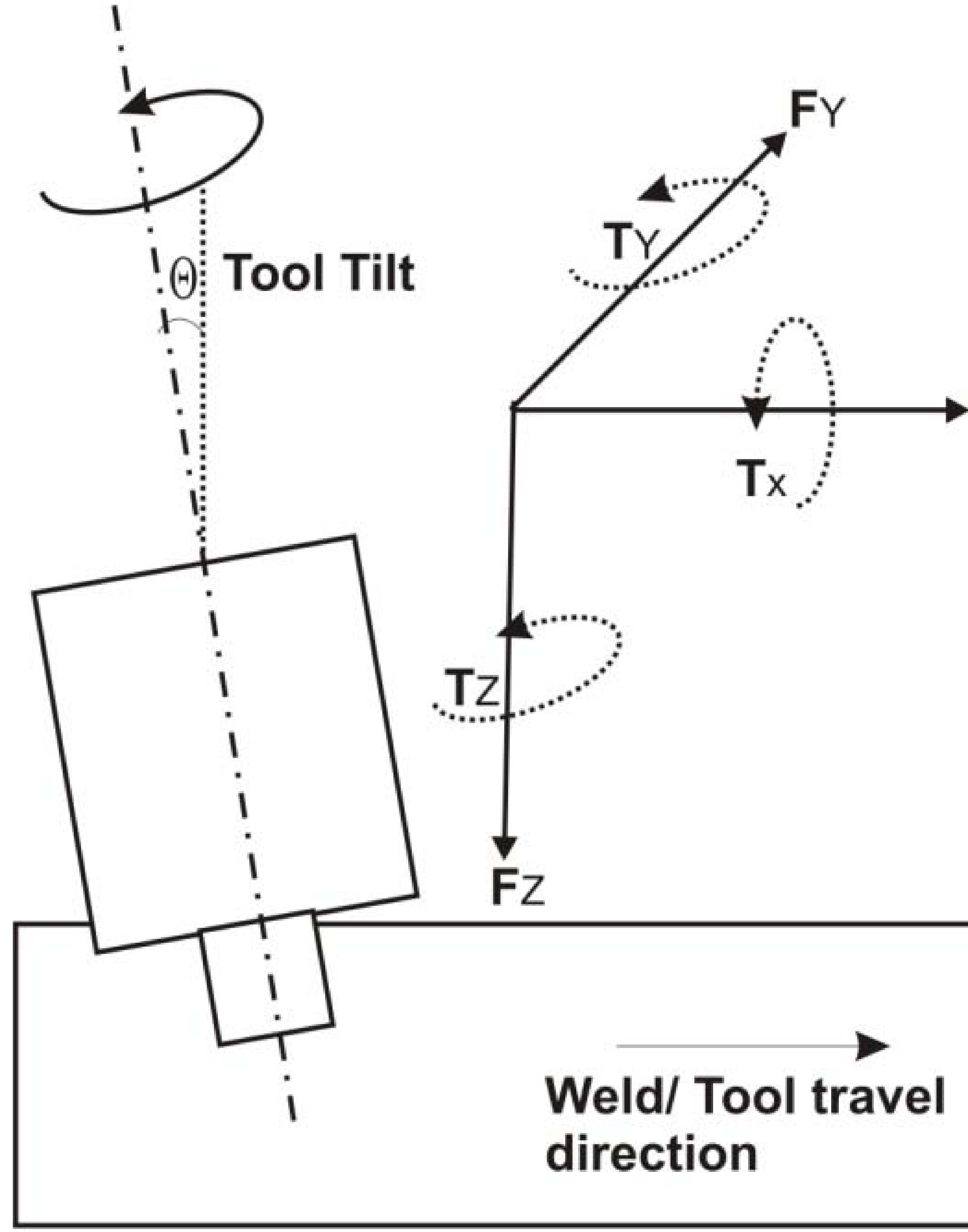

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Figure 3: Fig. 3 :

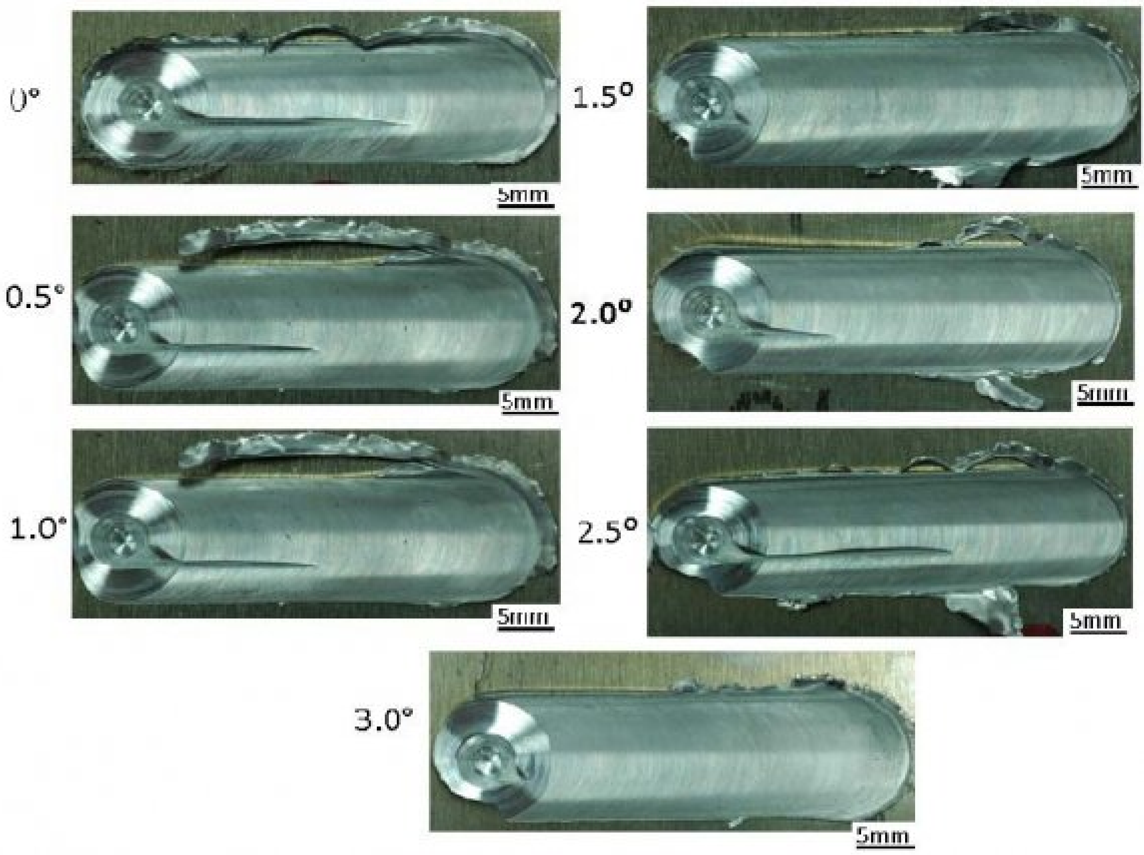

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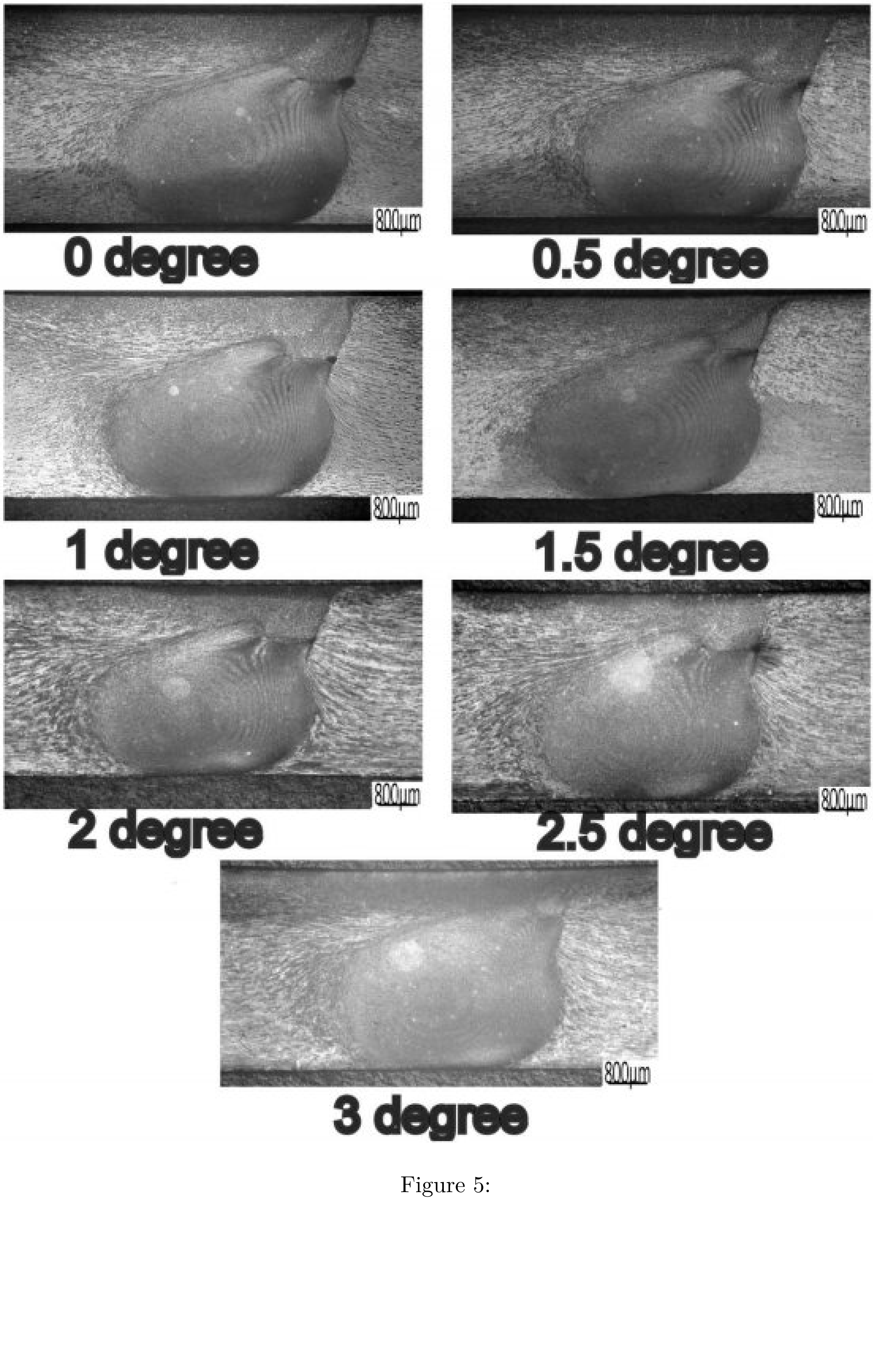
Figure 4: Fig. 4 :Fig. 5 :



800μm
0 degree
800μm
0.5 degree
800μm
1 degree
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1.5 degree
800μm
2 degree
800μm
2.5 degree
800μm
3 degree

Figure 5:

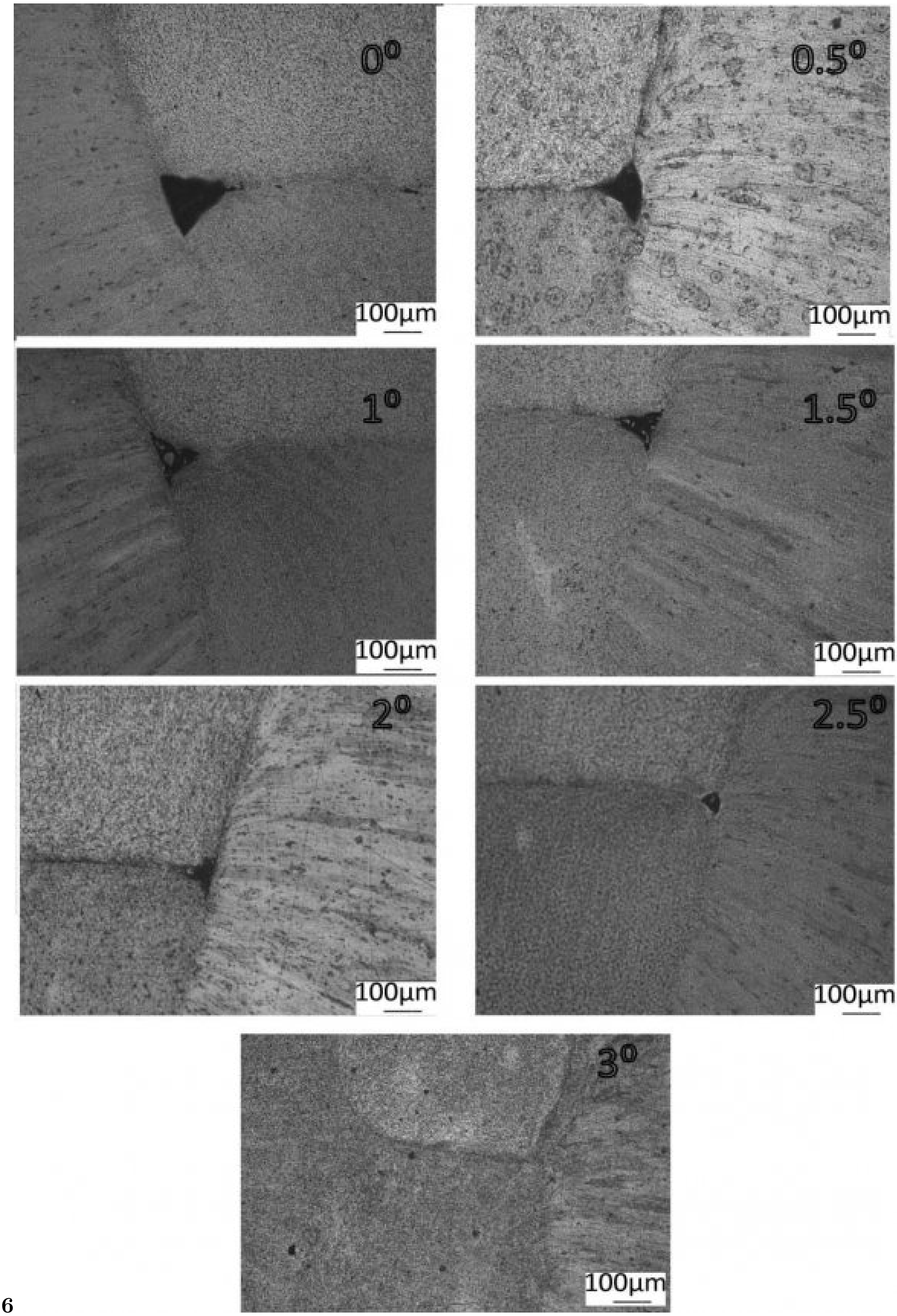

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Figure 6: Fig. 6 :

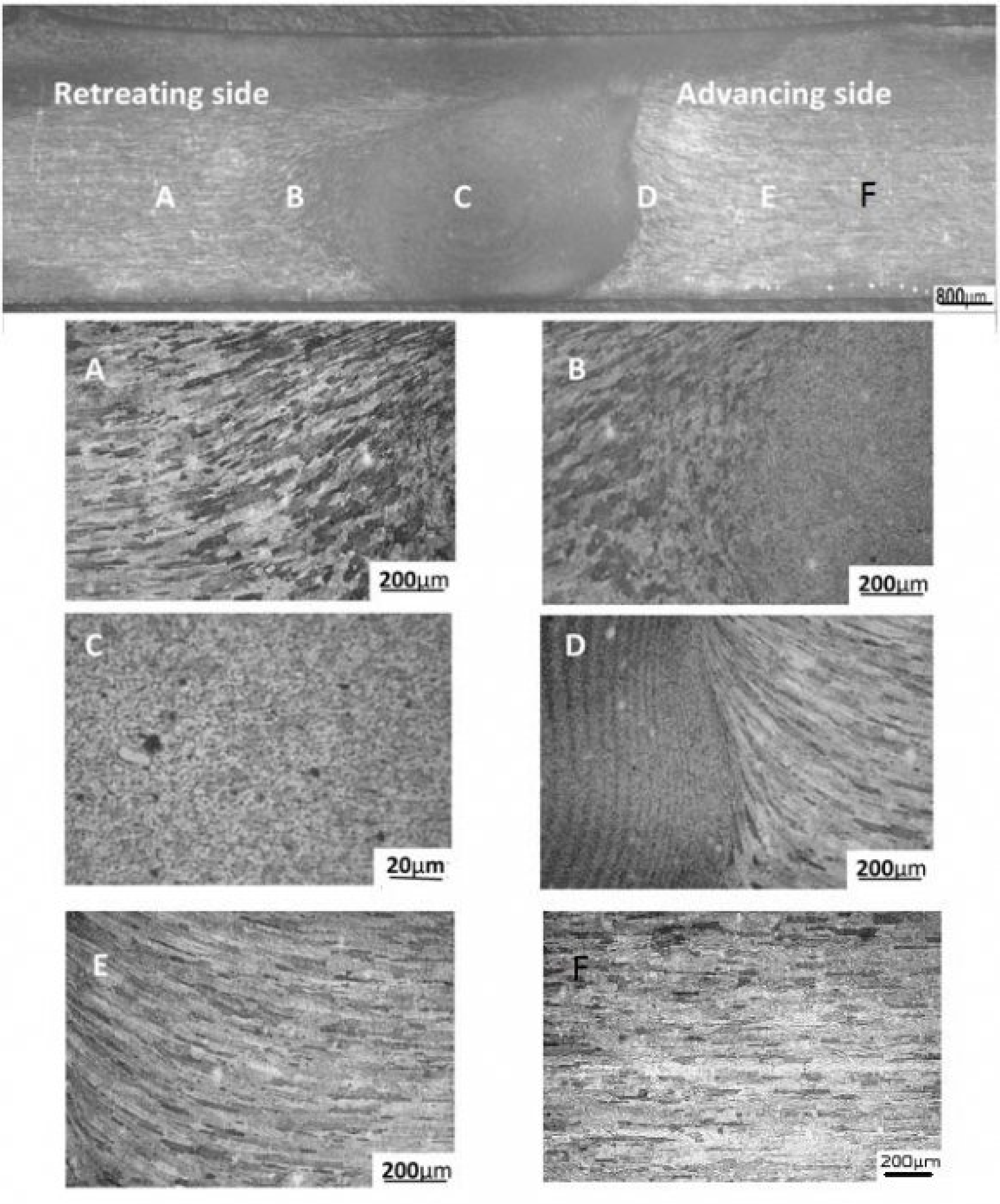

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Figure 7: Fig. 9 :

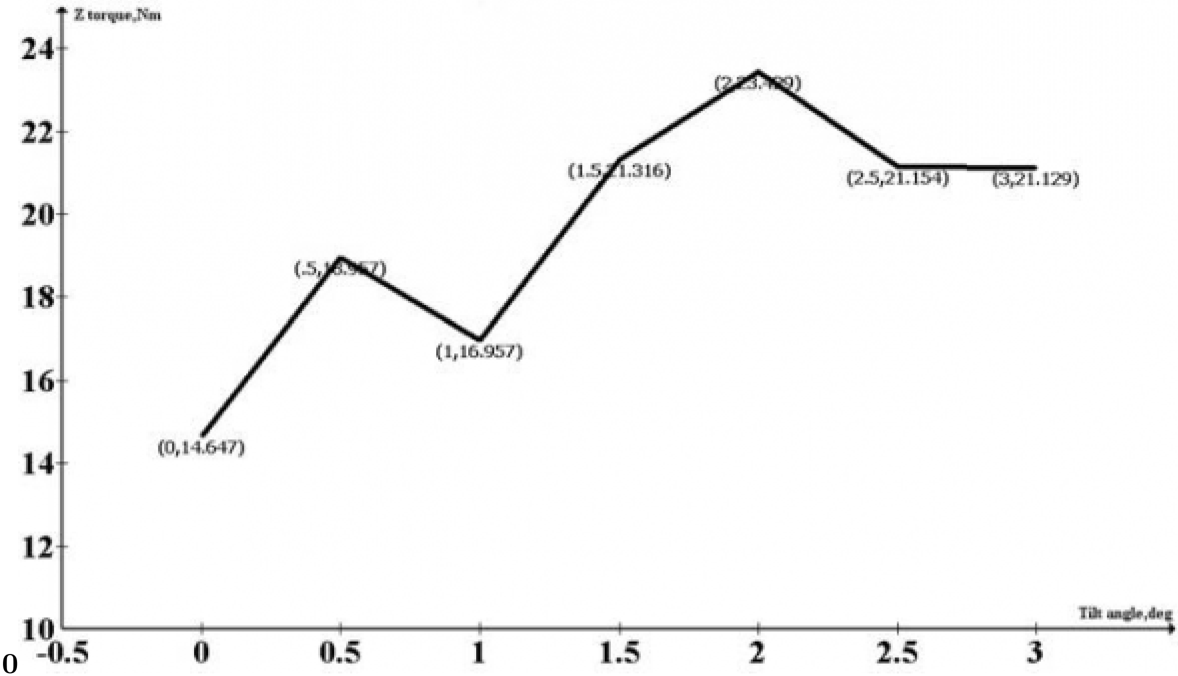
10 

Figure 8: Fig. 10 :

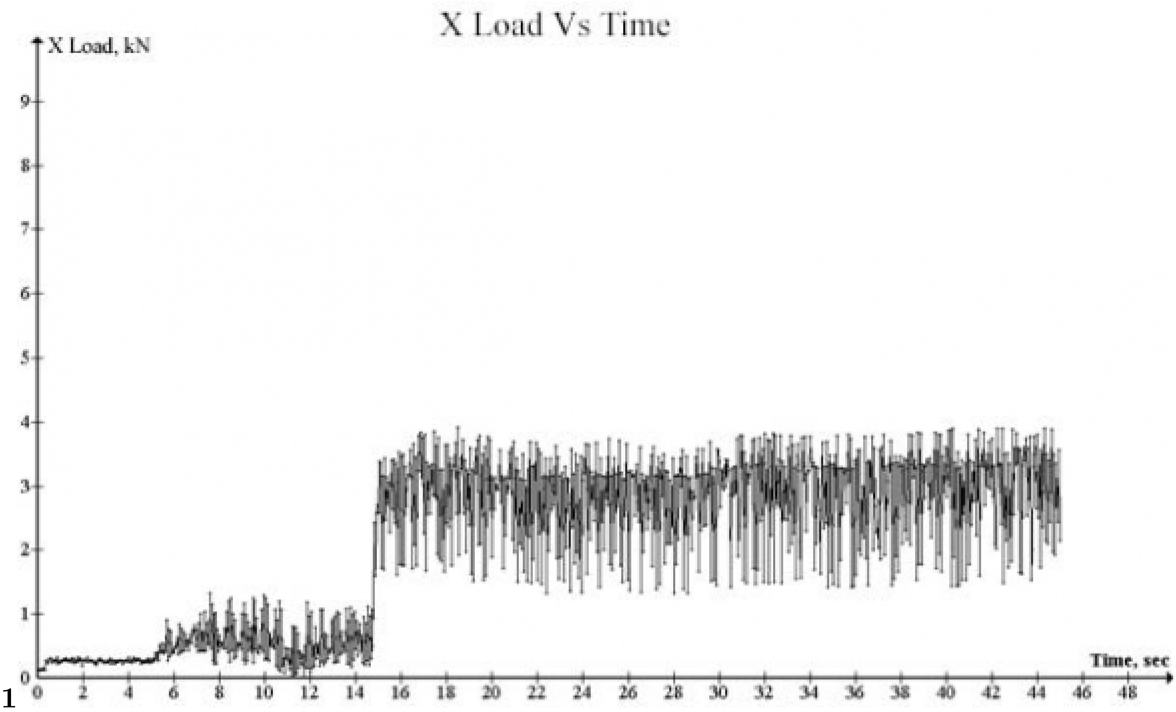
11 

Figure 9: Fig. 11 :

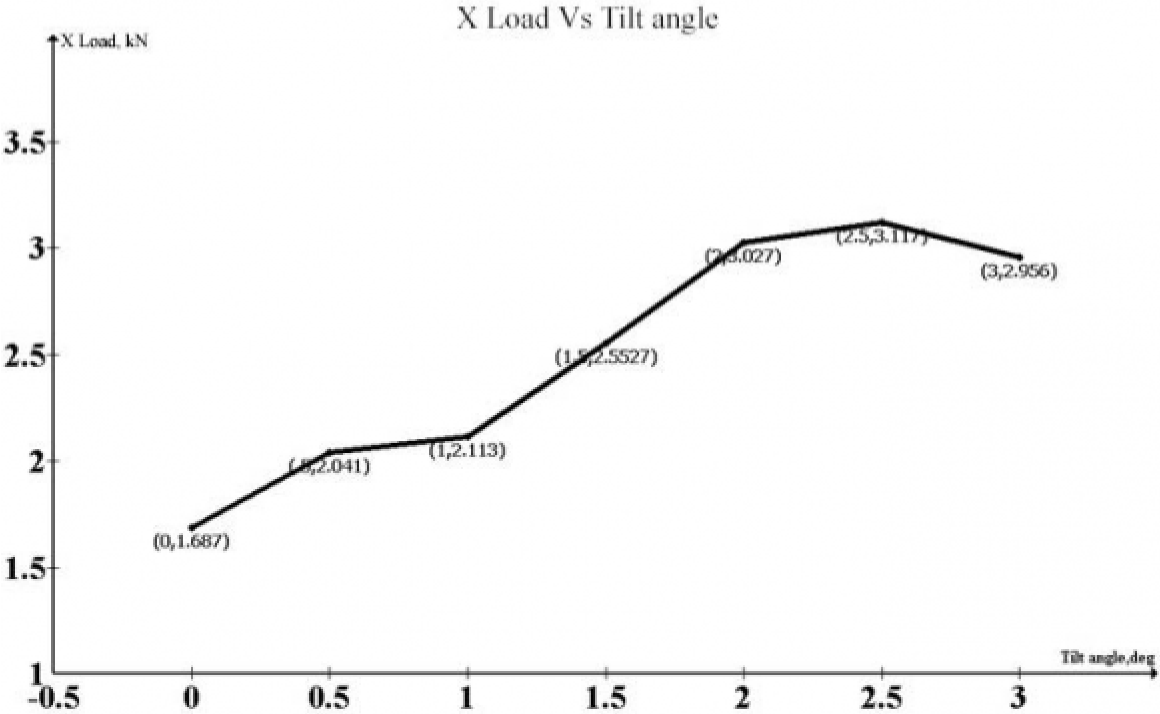


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Figure 10: Fig. 12 :

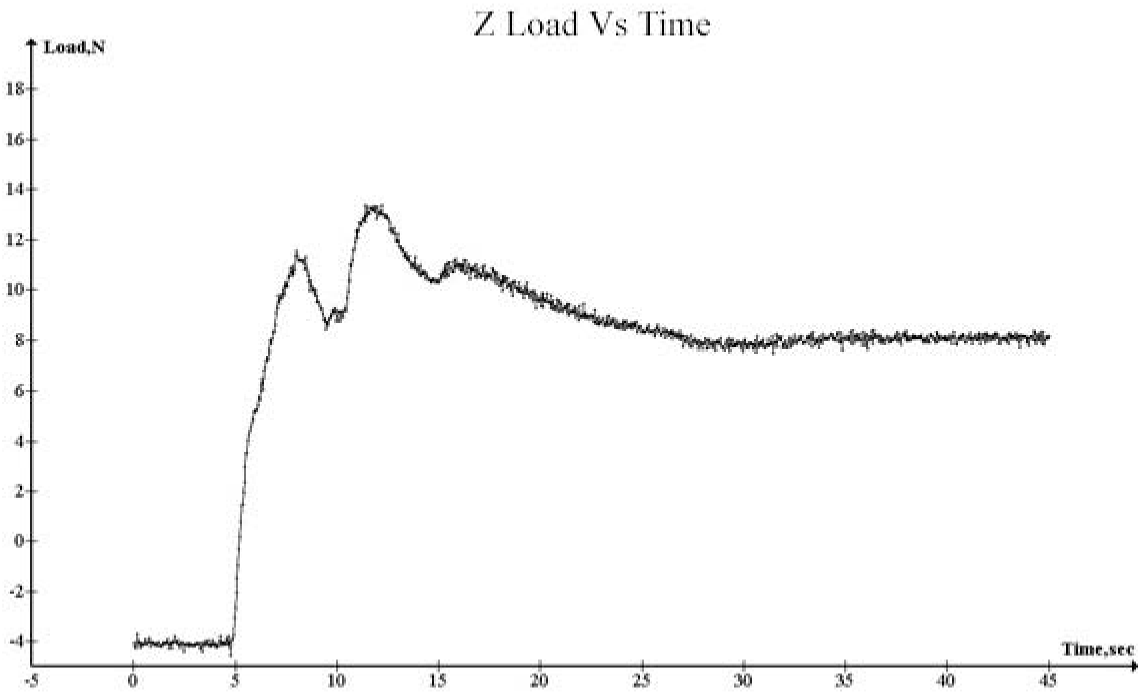

Figure 11: Conclusionsa)

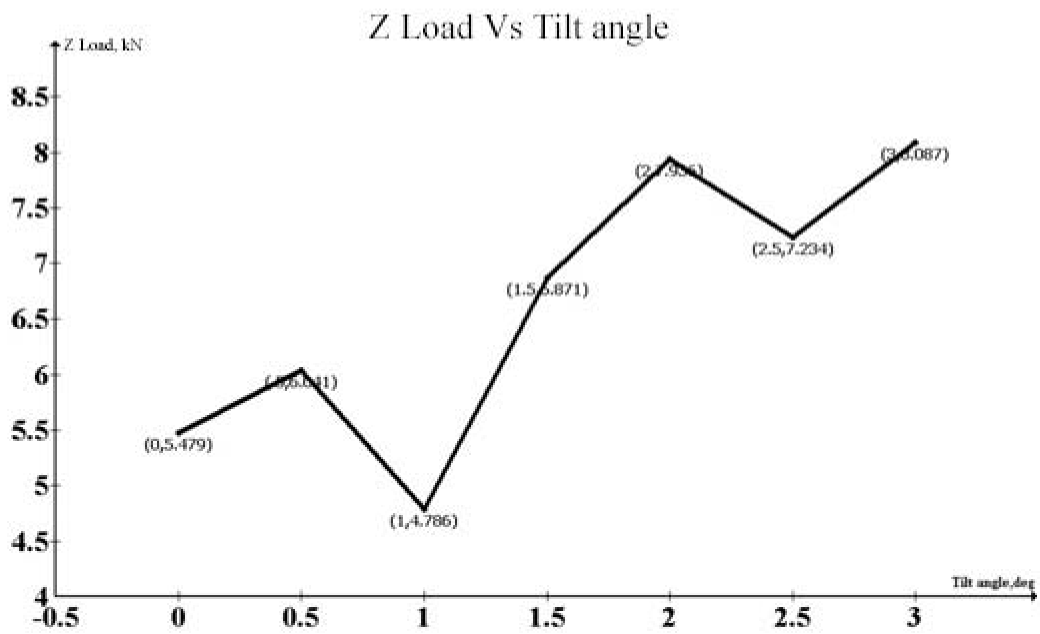

Figure 12:

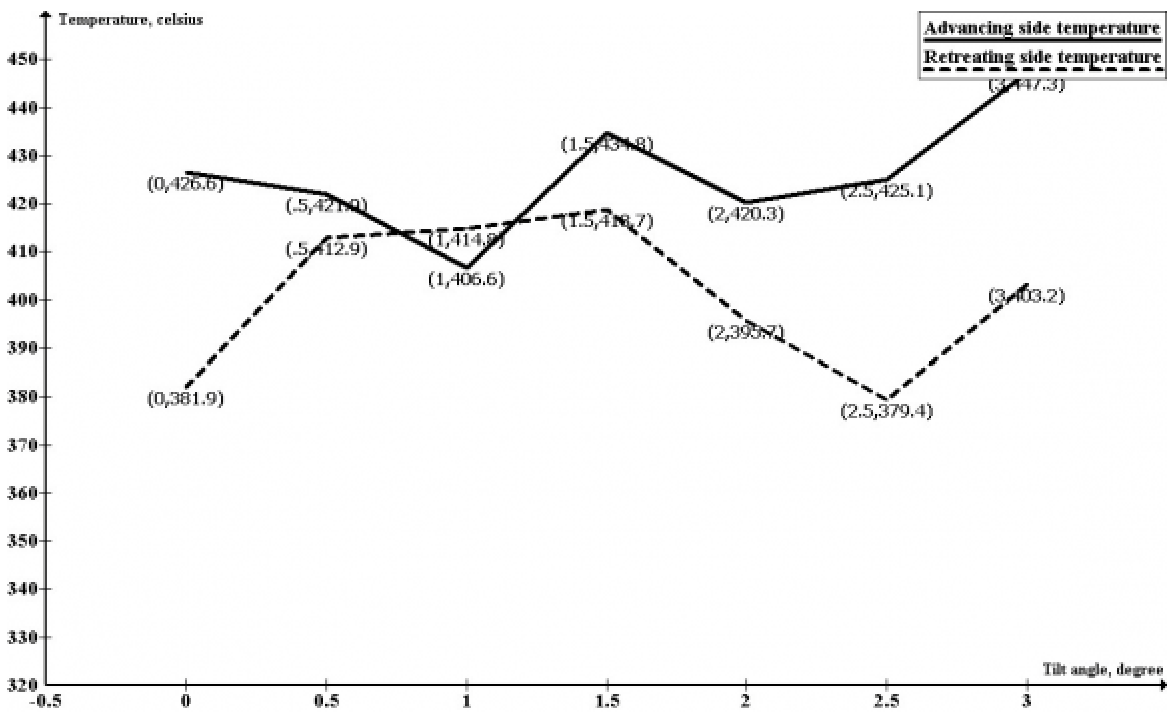

Figure 13:

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